

OpenCMISS-iron examples and tests used by *OpenCMISS* developers at University of Stuttgart, Germany

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1 INTRODUCTION

This document contains information about examples used for testing *OpenCMISS-iron*. Read: How-to¹ and [1].

1.1 Cmgui files for cmgui-2.9

1.2 Variations to consider

- Geometry and topology
 - 1D, 2D, 3D
 - Length, width, height
 - Number of elements
 - Interpolation order
 - Generated or user meshes
 - quad/hex or tri/tet meshes
- Initial conditions
- Load cases
 - Dirichlet BC
 - Neumann BC
 - Volume force
 - Mix of previous items
- Sources, sinks
- Time dependence
 - Static
 - Quasi-static
 - Dynamic
- Material laws
 - Linear
 - Nonlinear (Mooney-Rivlin, Neo-Hookean, Ogden, etc.)
 - Active (Stress, strain)
- Material parameters, anisotropy
- Solver
 - Direct
 - Iterative
- Test cases
 - Numerical reference data
 - Analytical solution
- A mix of previous items

¹ <https://bitbucket.org/hessenthaler/opencmisshowto>

1.3 Folder structure

TBD..

2 HOW TO WORK ON THIS DOCUMENT

In the Google Doc at https://docs.google.com/spreadsheets/d/1RGKj8vVPqQ-PH0UwMX_e9TAzqaYavKi0z0D4pKY9RGI/edit#gid=0 please indicate what you are working on or if a given example was finished

- no mark: to be done
- x: currently working on it
- xx: done

Initials	Full name
CB	Christian Bleiler
AH	Andreas Hessenthaler
TK	Thomas Klotz
AK	Aaron Krämer
BM	Benjamin Maier
SM	Sergio Morales
MM	Mylena Mordhorst
HS	Harry Saini

Table 1: Initials of people working on examples, in alphabetical order (surnames).

3 DIFFUSION EQUATION

3.1 Equation in general form

The governing equation is,

$$\partial_t u + \nabla \cdot [\sigma \nabla u] = f, \quad (1)$$

with conductivity tensor σ . The conductivity tensor is,

- defined in material coordinates (fibre direction),
- diagonal,
- defined per element.

3.2 Example-0001

Example uses generated regular meshes and solves a static problem, i.e., applies the boundary conditions in one step.

3.2.1 Mathematical model - 2D

We solve the following scalar equation,

$$\nabla \cdot \nabla u = 0 \quad \Omega = [0, 2] \times [0, 1], \quad (2)$$

with boundary conditions

$$u = 0 \quad x = y = 0, \quad (3)$$

$$u = 1 \quad x = 2, y = 1. \quad (4)$$

No material parameters to specify.

3.2.2 Mathematical model - 3D

We solve the following scalar equation,

$$\nabla \cdot \nabla u = 0 \quad \Omega = [0, 2] \times [0, 1] \times [0, 1], \quad (5)$$

with boundary conditions

$$u = 0 \quad x = y = z = 0, \quad (6)$$

$$u = 1 \quad x = 2, y = z = 1. \quad (7)$$

No material parameters to specify.

3.2.3 Computational model

- Commandline arguments are:
 - float: length along x-direction
 - float: length along y-direction
 - float: length along z-direction (set to zero for 2D)
 - integer: number of elements in x-direction
 - integer: number of elements in y-direction
 - integer: number of elements in z-direction (set to zero for 2D)
 - integer: interpolation order (1: linear; 2: quadratic)
 - integer: solver type (0: direct; 1: iterative)
- Commandline arguments for tests are:
 - 2.0 1.0 0.0 2 1 0 1 0
 - 2.0 1.0 0.0 4 2 0 1 0
 - 2.0 1.0 0.0 8 4 0 1 0
 - 2.0 1.0 0.0 2 1 0 2 0
 - 2.0 1.0 0.0 4 2 0 2 0
 - 2.0 1.0 0.0 8 4 0 2 0
 - 2.0 1.0 0.0 2 1 0 1 1
 - 2.0 1.0 0.0 4 2 0 1 1

```

2.0 1.0 0.0 8 4 0 1 1
2.0 1.0 0.0 2 1 0 2 1
2.0 1.0 0.0 4 2 0 2 1
2.0 1.0 0.0 8 4 0 2 1
2.0 1.0 1.0 2 1 1 1 0
2.0 1.0 1.0 4 2 2 1 0
2.0 1.0 1.0 8 4 4 1 0
2.0 1.0 1.0 2 1 1 2 0
2.0 1.0 1.0 4 2 2 2 0
2.0 1.0 1.0 8 4 4 2 0
2.0 1.0 1.0 2 1 1 1 1
2.0 1.0 1.0 4 2 2 1 1
2.0 1.0 1.0 8 4 4 1 1
2.0 1.0 1.0 2 1 1 2 1
2.0 1.0 1.0 4 2 2 2 1
2.0 1.0 1.0 8 4 4 2 1

```

3.2.4 Result summary

We use CHeart rev. 6292 to produce numerical reference solutions.

Passed tests: 24 / 24

No failed tests.

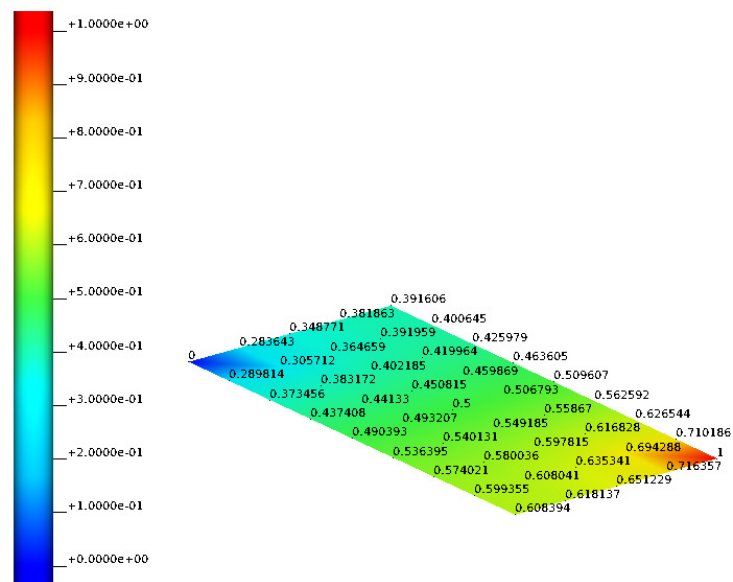


Figure 1: 2D results, iron reference w/ command line arguments [2.0 1.0 0.0 8 4 0 1 0].

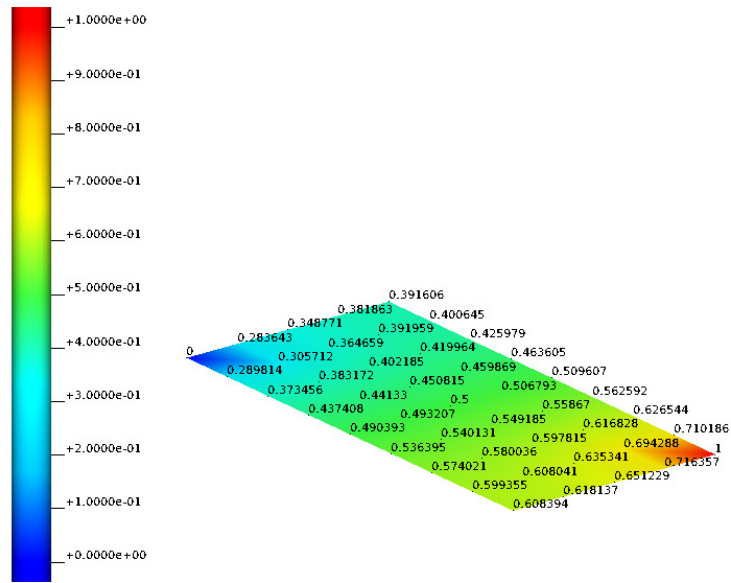


Figure 2: 2D results, current run w/ command line arguments [2.0 1.0 0.0 8 4 0 1 0].

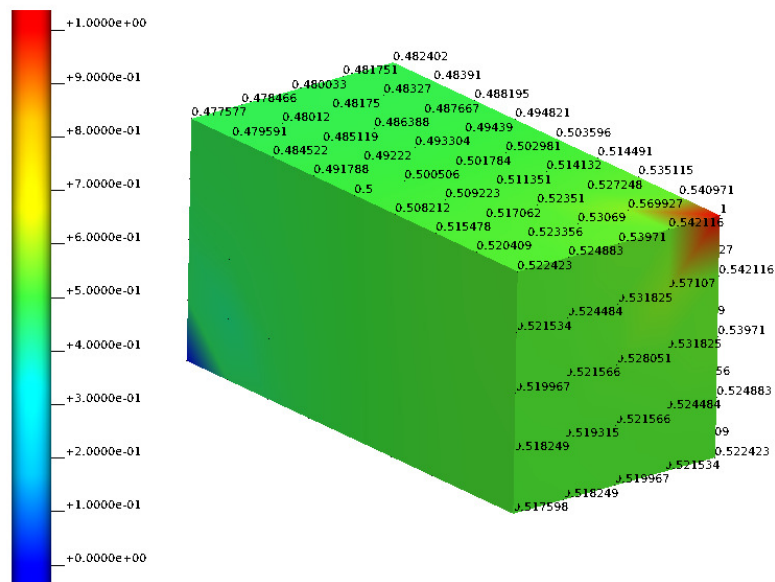


Figure 3: 3D results, iron reference w/ command line arguments [2.0 1.0 1.0 8 4 4 1 0].

3.3 Example-0001-u

Example uses user-defined regular meshes in CHeart mesh format and solves a static problem, i.e., applies the boundary conditions in one step.

3.3.1 Mathematical model - 2D

We solve the following scalar equation,

$$\nabla \cdot \nabla u = 0 \quad \Omega = [0, 2] \times [0, 1], \quad (8)$$

with boundary conditions

$$u = 0 \quad x = y = 0, \quad (9)$$

$$u = 1 \quad x = 2, y = 1. \quad (10)$$

No material parameters to specify.

3.3.2 Mathematical model - 3D

We solve the following scalar equation,

$$\nabla \cdot \nabla u = 0 \quad \Omega = [0, 2] \times [0, 1] \times [0, 1], \quad (11)$$

with boundary conditions

$$u = 0 \quad x = y = z = 0, \quad (12)$$

$$u = 1 \quad x = 2, y = z = 1. \quad (13)$$

No material parameters to specify.

3.3.3 Computational model

- Commandline arguments are:
 - float: length along x-direction
 - float: length along y-direction
 - float: length along z-direction (set to zero for 2D)
 - integer: number of elements in x-direction
 - integer: number of elements in y-direction
 - integer: number of elements in z-direction (set to zero for 2D)
 - integer: interpolation order (1: linear; 2: quadratic)
 - integer: solver type (0: direct; 1: iterative)
- Commandline arguments for tests are:
 - 2.0 1.0 0.0 2 1 0 1 0
 - 2.0 1.0 0.0 4 2 0 1 0
 - 2.0 1.0 0.0 8 4 0 1 0
 - 2.0 1.0 0.0 2 1 0 2 0
 - 2.0 1.0 0.0 4 2 0 2 0
 - 2.0 1.0 0.0 8 4 0 2 0
 - 2.0 1.0 0.0 2 1 0 1 1
 - 2.0 1.0 0.0 4 2 0 1 1

```

2.0 1.0 0.0 8 4 0 1 1
2.0 1.0 0.0 2 1 0 2 1
2.0 1.0 0.0 4 2 0 2 1
2.0 1.0 0.0 8 4 0 2 1
2.0 1.0 1.0 2 1 1 1 0
2.0 1.0 1.0 4 2 2 1 0
2.0 1.0 1.0 8 4 4 1 0
2.0 1.0 1.0 2 1 1 2 0
2.0 1.0 1.0 4 2 2 2 0
2.0 1.0 1.0 8 4 4 2 0
2.0 1.0 1.0 2 1 1 1 1
2.0 1.0 1.0 4 2 2 1 1
2.0 1.0 1.0 8 4 4 1 1
2.0 1.0 1.0 2 1 1 2 1
2.0 1.0 1.0 4 2 2 2 1
2.0 1.0 1.0 8 4 4 2 1

```

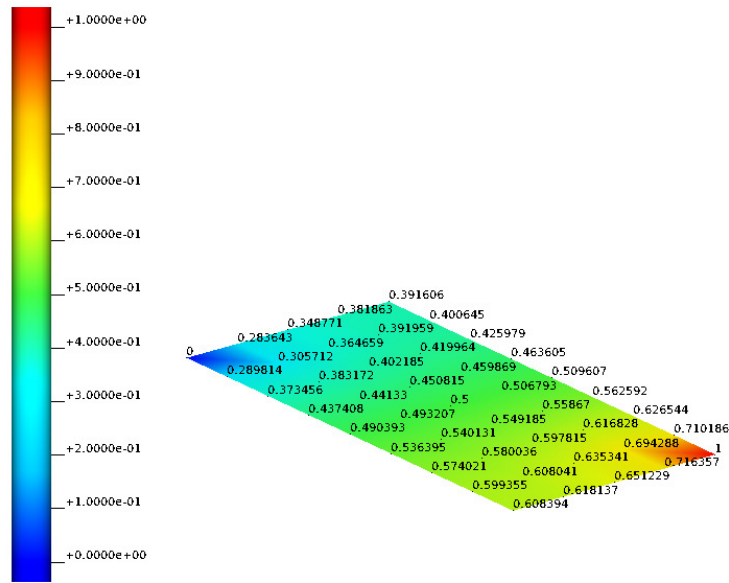
- Note: Binary uses command line arguments to search for the relevant mesh files.

3.3.4 *Result summary*

We use CHeart rev. 6292 to produce numerical reference solutions.

Passed tests: 24 / 24

No failed tests.



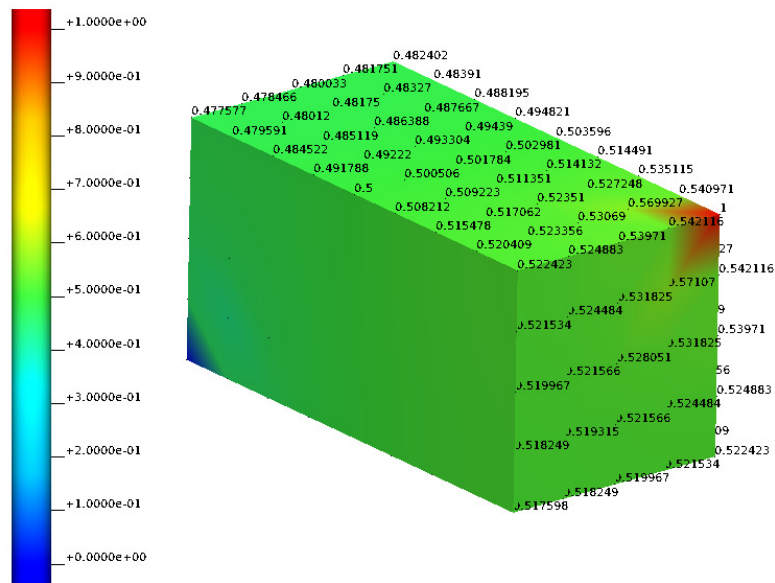


Figure 7: 3D results, iron reference w/ command line arguments [2.0 1.0 1.0 8 4 1 0].

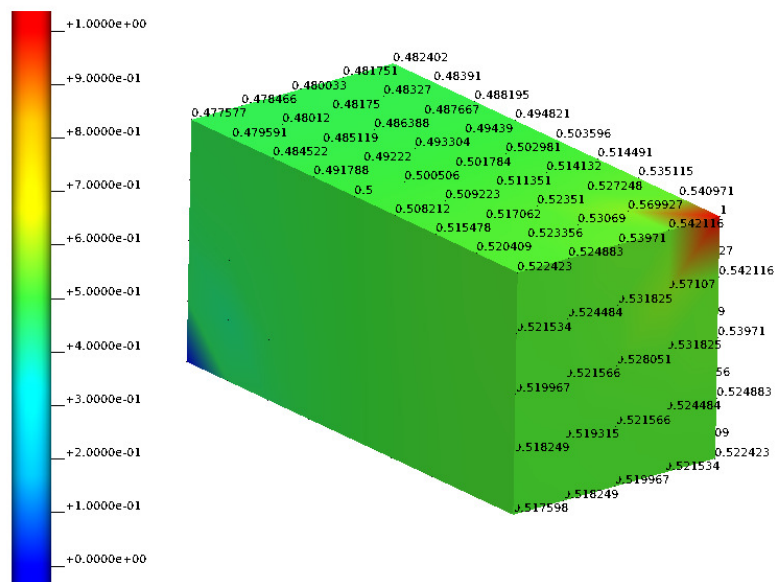


Figure 8: 3D results, current run w/ command line arguments [2.0 1.0 1.0 8 4 4 1 0].

3.4 Example-0011

Example uses generated regular meshes and solves a static problem, i.e., applies the boundary conditions in one step.

3.4.1 Mathematical model - 2D

We solve the following scalar equation,

$$\nabla \cdot [\sigma \nabla u] = 0 \quad \Omega = [0, 2] \times [0, 1], \quad (14)$$

with boundary conditions

$$u = 0 \quad x = y = 0, \quad (15)$$

$$u = 1 \quad x = 2, y = 1. \quad (16)$$

The conductivity tensor is defined as,

$$\sigma(x, t) = \sigma = \mathbf{I}. \quad (17)$$

3.4.2 Mathematical model - 3D

We solve the following scalar equation,

$$\nabla \cdot [\sigma \nabla u] = 0 \quad \Omega = [0, 2] \times [0, 1] \times [0, 1], \quad (18)$$

with boundary conditions

$$u = 0 \quad x = y = z = 0, \quad (19)$$

$$u = 1 \quad x = 2, y = z = 1. \quad (20)$$

The conductivity tensor is defined as,

$$\sigma(x, t) = \sigma = \mathbf{I}. \quad (21)$$

3.4.3 Computational model

- Commandline arguments are:
 - float: length along x-direction
 - float: length along y-direction
 - float: length along z-direction (set to zero for 2D)
 - integer: number of elements in x-direction
 - integer: number of elements in y-direction
 - integer: number of elements in z-direction (set to zero for 2D)
 - integer: interpolation order (1: linear; 2: quadratic)
 - integer: solver type (0: direct; 1: iterative)
 - float: σ_{11}
 - float: σ_{22}
 - float: σ_{33} (ignored for 2D)

- Commandline arguments for tests are:

```

2.0 1.0 0.0 2 1 0 1 0 1 1
2.0 1.0 0.0 4 2 0 1 0 1 1
2.0 1.0 0.0 8 4 0 1 0 1 1
2.0 1.0 0.0 2 1 0 2 0 1 1
2.0 1.0 0.0 4 2 0 2 0 1 1
2.0 1.0 0.0 8 4 0 2 0 1 1
2.0 1.0 0.0 2 1 0 1 1 1 1
2.0 1.0 0.0 4 2 0 1 1 1 1
2.0 1.0 0.0 8 4 0 1 1 1 1
2.0 1.0 0.0 2 1 0 2 1 1 1
2.0 1.0 0.0 4 2 0 2 1 1 1
2.0 1.0 0.0 8 4 0 2 1 1 1
2.0 1.0 1.0 2 1 1 1 0 1 1 1
2.0 1.0 1.0 4 2 2 1 0 1 1 1
2.0 1.0 1.0 8 4 4 1 0 1 1 1
2.0 1.0 1.0 2 1 1 2 0 1 1 1
2.0 1.0 1.0 4 2 2 2 0 1 1 1
2.0 1.0 1.0 8 4 4 2 0 1 1 1
2.0 1.0 1.0 2 1 1 1 1 1 1 1
2.0 1.0 1.0 4 2 2 1 1 1 1 1
2.0 1.0 1.0 8 4 4 1 1 1 1 1
2.0 1.0 1.0 2 1 1 2 1 1 1 1
2.0 1.0 1.0 4 2 2 2 1 1 1 1
2.0 1.0 1.0 8 4 4 2 1 1 1 1

```

3.4.4 *Result summary*

We use CHeart rev. 6292 to produce numerical reference solutions.

Passed tests: 24 / 24

No failed tests.

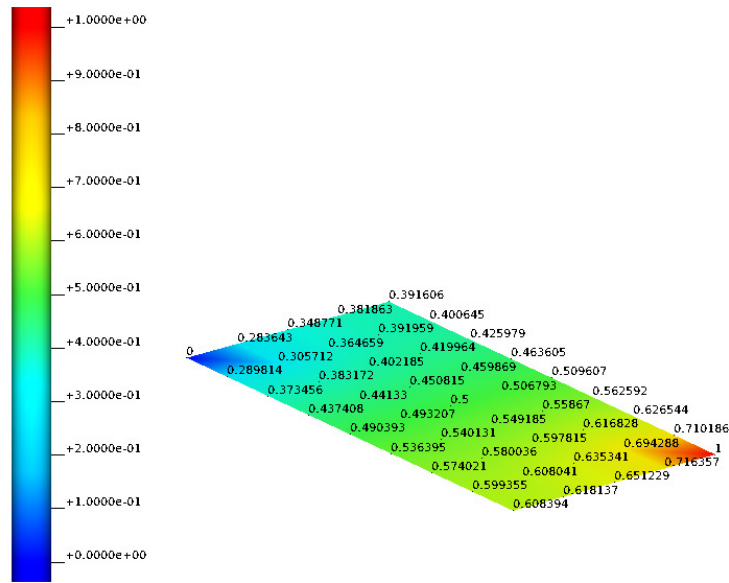


Figure 9: 2D results, iron reference w/ command line arguments [2.0 1.0 0.0 8 4 0 1 0 1 1].

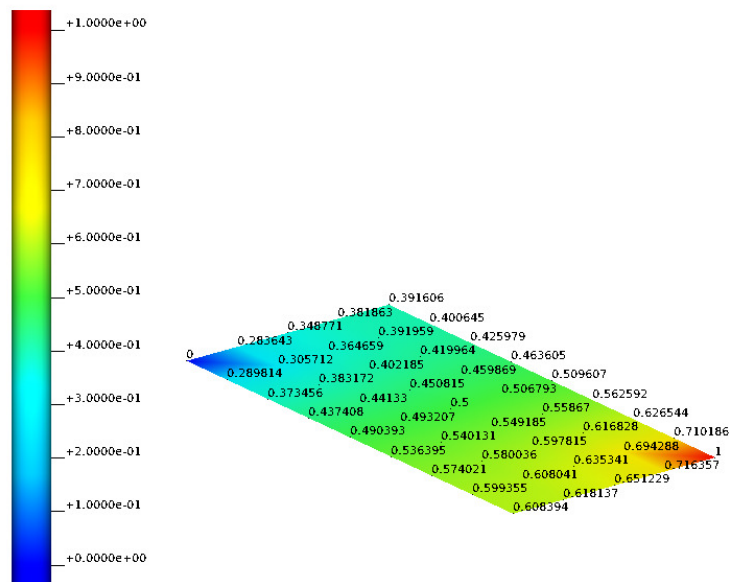


Figure 10: 2D results, current run w/ command line arguments [2.0 1.0 0.0 8 4 0 1 0 1 1].

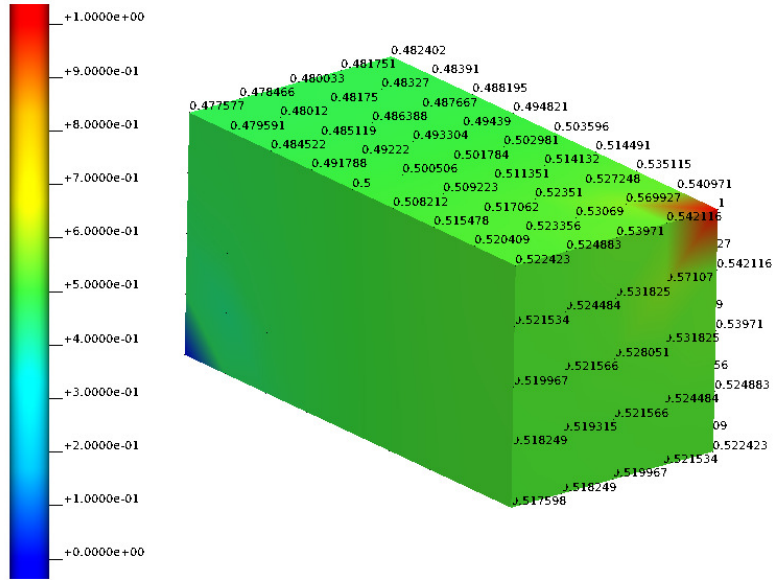


Figure 11: 3D results, iron reference w/ command line arguments [2.0 1.0 1.0 8 4 4 1 0 1 1 1].

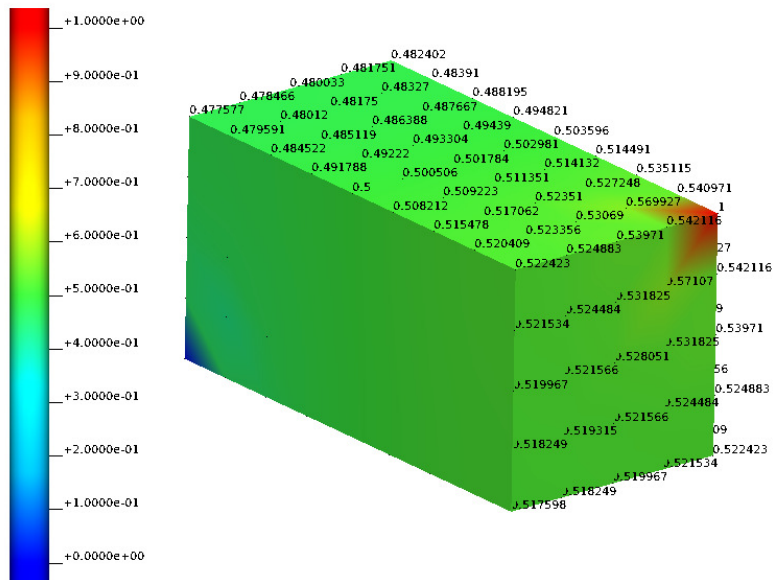


Figure 12: 3D results, current run w/ command line arguments [2.0 1.0 1.0 8 4 4 1 0 1 1 1].

4 LINEAR ELASTICITY

4.1 Equation in general form

$$\partial_{tt}\mathbf{u} + \nabla \cdot \boldsymbol{\sigma}(\mathbf{u}, t) = \mathbf{f}(\mathbf{u}, t) \quad (22)$$

4.2 Example-0101

4.2.1 Mathematical model

We solve the following equation,

$$\nabla \cdot \boldsymbol{\sigma}(\mathbf{u}, t) = \mathbf{0} \quad \Omega = [0, 160] \times [0, 120], t \in [0, 5], \quad (23)$$

with time step size $\Delta_t = 1$ and boundary conditions

$$\dots \quad \dots, \quad (24)$$

$$\dots \quad \dots \quad (25)$$

2D: specify thickness, Young's modulus and Poisson's ratio.

4.2.2 Computational model

- Length, width, height
- Direct/iterative solver
- Generated/user mesh
- Number of elements
- Interpolation order
- Number of solver steps (time steps, load steps)

4.2.3 Results

Figure 13: Results, analytical solution.

4.2.4 Validation

CHeart rev. 6328, Abaqus 2017, analytical reference solution, whatever...

Figure 14: Results, Abaqus reference.

Figure 15: Results, iron reference.

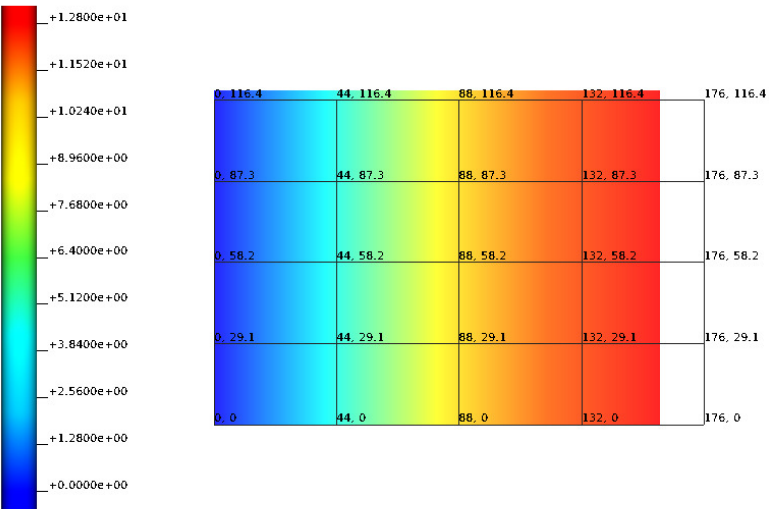


Figure 16: Results, current run.

5 FINITE ELASTICITY

6 NAVIER-STOKES FLOW

7 MONODOMAIN

8 CELLML MODEL

REFERENCES

- [1] Chris Bradley, Andy Bowery, Randall Britten, Vincent Budelmann, Oscar Camara, Richard Christie, Andrew Cookson, Alejandro F Frangi, Thiranjia Babarenda Gamage, Thomas Heidlauf, et al. Openmiss: a multi-physics & multi-scale computational infrastructure for the vph/-physiome project. *Progress in biophysics and molecular biology*, 107(1):32–47, 2011.